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Study on Shaking Table Model Test Scheme of Tunnel Subjected to Near-Fault Pulse-Like Ground Motions

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Abstract

Based on the Natural Science Foundation Project of China "Theoretical study on shock absorption of tunnel subjected to near-fault pulse-like ground motions" (51078324), this research conducts a shaking table model test scheme study to explore the seismic responses of tunnel subjected to near-fault pulse-like ground motions. The test which includes the decision of model similarity ratio, the design of model box and the treatment of boundary, the making of model, the layout of test points and the loading scheme of seismic wave and so on is introduced in detail in this paper. The test focuses on the rule and character of the dynamic response of the tunnel subjected to near-fault pulse-like ground motions. The test results show that the near-fault pulse-like ground motions is destructive. With seismic waves upward propagating, the seismic response of rock and soil is increasing. The tunnel linings were severely damaged.

1. Introduction

A large number of earthquake damage survey showed that the tunnel had a good ability to withstand earthquake damage, but as the result of Wenchuan earthquake in China in 2008, most of the tunnels in Dujiangyan-Wenchuan Highway were subject to varying degrees of damage, in which 73% of the tunnels were damaged severely, especially in the tunnel portal section and the section in fault formation. Near-fault pulse-like ground motions with high peak accelerations and long period velocity pulses are highly destructive. A lot of data statistics show that the tunnels subjected to near-fault ground motions have suffered more serious damages. In addition, it plays a pivotal role to ensure smooth traffic for the tunnel. It is undoubtedly deadly for disaster relief if the tunnels collapse and lose function. Therefore, it is necessary to carry out researches on the tunnel structure subjected to near-fault pulse-type ground motions and to analyze the structural dynamic response of tunnel lining, so as to lay the foundation of shock absorption studies on near-fault tunnel. This paper made a thorough discussion on the specific test scheme and analyzed the test data and failure mode of the tunnel lining.

2. Test Overview

Relying on the Natural Science Foundation Project of China "Theoretical study on shock absorption of tunnel subjected to near-fault pulse-like ground motions", the test was conducted in the State Key Laboratory of Structural Dynamic with earthquake simulation test seismic array system in Chongqing Communications Research and Design Institute. This large high-performance three-axis earthquake simulation seismic array system is the only one that consists of a fixed station and a mobile station all over the world. The level of technology and performance of the system which uses the world's most advanced digital control systems and software are at the international advanced level. The supporting data acquisition, vibration measurement and analysis system are currently the world's most advanced. The three-axial shaking table system is shown in Figure 1. System parameters and technical parameters are shown in Table 1. This model test used the fixed station of the seismic array system. The acceleration, strain and earth pressure dynamic data acquisition is achieved by the 128 channel. Data collecting, storing and processing is running by the vibration measurement and analysis system with hardware of the U.S. HP's VXI system and software of the Belgian company's LMS CADA-X software. It is one of the world's most powerful and most technologically advanced dynamic data acquisition and analysis of vibration test systems. The main purpose of the test is to analyze and summarize the law of tunnel dynamic response, failure mechanism and failure mode of lining structure when the tunnel is subjected to near-fault pulse-like ground motions, and to lay the foundation of presenting the shock absorption theory of near fault tunnel.

Figure 1. Three-axial shaking table system

Table 1. Main parameters of shaking table system

Technical Parameters		Fixed station	Mobile station
Table size/m×m		3×6	3×6
Maximum specimen weight/ton		35	35
Maximum overturning moment /kN·m		700	700
Maximum turning moment /kN·m		350	350
Operating frequency range /Hz		0.1～50	0.1～50
X-direction movable distance /m		0.0	2.0～20.0
Maximum displacement /mm	*X* direction	±150	±150
	Y direction	±150	±150
	Z direction	±150	±150
Maximum velocity /(mm/s)	*X* direction	±800	±800
	Y direction	±800	±800
	Z direction	±600	±600
Maximum acceleration /g	*X* direction	±1.0	±1.0
	Y direction	±1.0	±1.0
	Z direction	±1.0	±1.0

3. Model Similarity Ratio

Many experimental studies have shown that it is difficult to fully meet the similarity theorem in dynamic model tests due to the complexity of soil traits. We can use approximation similarity method to determine similarity relationships according to the test purposes and the main factors. Moreover, under the current experimental conditions, the use of artificial methods to simulate the effects of gravity mass of rock and soil is quite difficult, therefore, this test uses gravity distortion model.

Considering the shaking table size, bearing capacity, boundary effect range and other factors, the model similarity ratio refer to Table 2.

Table 2. Similarity relations and rations of physical parameters

Physical parameters	Symbol	Dimension	Similarity ratio	Remark
Length	C_L	L	30	Basic similarity ratio
Modulus of elasticity	C_E	FL^{-2}	30	Basic similarity ratio
Strain	C_ζ	—	1	
Poisson's ratio	C_v	—	1	Basic similarity ratio
Density	C_ρ	FT^2L^{-4}	1	
Stress	C_σ	FL^{-2}	30	
Mass	C_m	$FL^{-1}T^2$	27000	
Time	C_t	T	5.48	
Damping	C_c	$FL^{-1}T$	4929.50	
Frequency	C_f	T^{1}	0.18	
Cycle	C_T	T	5.48	
Displacement	C_u	L	30	
Velocity	C_v	LT^{1}	5.48	
Acceleration	C_a	LT^{-2}	1	
Gravitational Acceleration	C_h	LT^{-2}	1	
Area loads	C_q	FL^{-2}	30	

4. Model Box Design and Boundaries

The model box in the test was designed with the following factors:

(1) Solid structure, to avoid losing stability and not to damage the box in the intense vibrating process;

(2) Clear boundary conditions;

(3) The natural frequency of the model box deviating as much as possible from the frequency of soil in order to avoid resonance phenomenon;

(4) Model box size matches the size of the shaking table.

Taking the test and equipment into account, the model box is designed as a cuboid structure with size 3 m × 2.7 m × 2.45 m, in which the length along the tunnel longitudinally is 3 m, the lateral width 2.7 m, and the height 2.45 m.

Model box uses rigidly fixed boundaries with flexible material lined around the box. Its main frame is welded together with 7 equilateral angle steels, surrounded by 5 mm steel plates as enclosure. Considering the convenience of pouring the surrounding rock model, the model box is divided into five layers. The first layer has the thickness of 450 mm, and the other layers have the thickness of 500 mm. 20 M20 bolts are used to rivet every two adjacent layers. Bevel angle steels are added parallel to the sides of the model box to improve the overall vibration frequency to prevent box resonance with the model. Section of the base perimeter uses 100 mm × 50 mm steel frame, as the same, the bottom crossbar of the model box uses l00 mm × 50 mm steel welded trellis. The base reserves bolt holes to connect with the shaking table. Model box front and back (tunnel entrance and exit) reserve 300 × 300 mm square holes for observing. The real model box is shown in Figure 2.

Figure 2. An external view of the model box

After all, the soil of underground structure model test is finite. To make the semi-infinite soil be finite relates to the issue of artificial boundary treatment on which many scholars have done in-depth study.

If the soil contacts the model box sidewalls smoothly, the contacted interfaces have little effect on the soil. On the contrary, the contacted interfaces have a greater impact on the soil if the model box sidewalls are rough. Therefore, when dealing with the boundary of the model box, the sidewalls should be guaranteed smooth so as to reduce experimental error. In the bottom of the box, a layer of crushed stone is paved to increase the soil's friction resistance, and then to prevent relative sliding between the soil and the bottom of the box.

A layer of polystyrene foam board is set around the box sidewalls in order to simulate the semi-infinite soil's deformation and resilient recovery. Under the condition that other parameters are the same, the lighter the foam board is, the better the effects are.

At first, the boundary physical parameters-stiffness and damping should be defined based on three-dimensional viscoelastic artificial boundary equations. Then select the appropriate polystyrene foam board according to the parameters. For the polystyrene foam board, equivalent stiffness and equivalent damping model created by Soong can be recommended to determine the equivalent stiffness k_d and equivalent damping c_d by test methods.

$$c_{\mathrm{d}} = \frac{G''V}{\omega h^2}, \quad k_{\mathrm{d}} = \frac{G'V}{h^2} \tag{1}$$

Where G' is the shear modulus storage of polystyrene foam material; G'' is the shear modulus loss; h is the thickness of the polystyrene foam boards; V is the volume; ω is the natural frequency of model box and soil.

Thereby the determined thickness of the polystyrene foam board is 22.5 cm.

When the ratio of the model box's natural frequency and the soil's natural frequency is between 0.75 and 1.25, resonance phenomenon will be happen. This ratio must be beyond this range in order to prevent this phenomenon. The first-order natural frequency of the model box is 13.72 Hz which is obtained by finite element analysis calculation and that deviate far from the first-order natural frequency of the soil. It is evident that there will be no resonance between the model box and the soil.

5. The Similar Material of Surrounding Rock and the Modeling

After a lot of ratio test, finally we choose gypsum mixes as similar material of surrounding rock, namely: aggregate - quartz; cementing material - gypsum; other materials - water; filling additive - barite powder (barium sulfate).

As the thickness of tunnel lining prototype is 60 cm, based on the similarity theory, model tunnel lining's thickness is 20 mm. The portal section is divided into six sections (each length 400 mm), the deeper buried section is divided into seven sections (the first six parts each length 400 mm, last one 200 mm). In the reinforced concrete, gypsum is used to simulate the concrete and φ0.7 mm woven barbed wire to steel bars. The simulated linings are prefabricated by a particular mold.

Before making the simulated linings, the mold inner wall is smeared a layer of oil, then pour the prepared gypsum slurry into the mold, standing for half an hour or so to release. And cure 7 days or so to reach a permanent strength at room temperature (25 ~ 35 °C).

We choose gypsum as similar material of surrounding rock and lining, but gypsum can be affected by air humidity and temperature evidently. Especially humidity, we have got great different physical parameters in different weather conditions. To avoid this, we should strictly control the curing of gypsum specimen, and test under the same environmental conditions as possible. A completed specimen can be protected by a thin layer of varnish. Furthermore, different batches and types of similar materials have physical parameters error, effective control is necessary in the test.

Wooden mold has large deformation in contact with water, and not conducive to recycling, so we use steel material. The steel mold is shown in Figure 3.

Figure 3. Steel mold of lining model making

6. Testing Apparatus and Test Points Arrangement

The test data to be collected include acceleration, strain and displacement of lining structure, the contact pressure of surrounding rock and lining structure, the acceleration of side slope in the portal section and acceleration and displacement of the surface above the tunnel.

Optional sensors include: BY-3-type soil micro resistance strain pressure gauge, resistance strain sensor, CA-YD-152-type piezoelectric acceleration sensors and displacement sensors.

In this shaking table test, the arrangement of the sensors must meet the following principles:

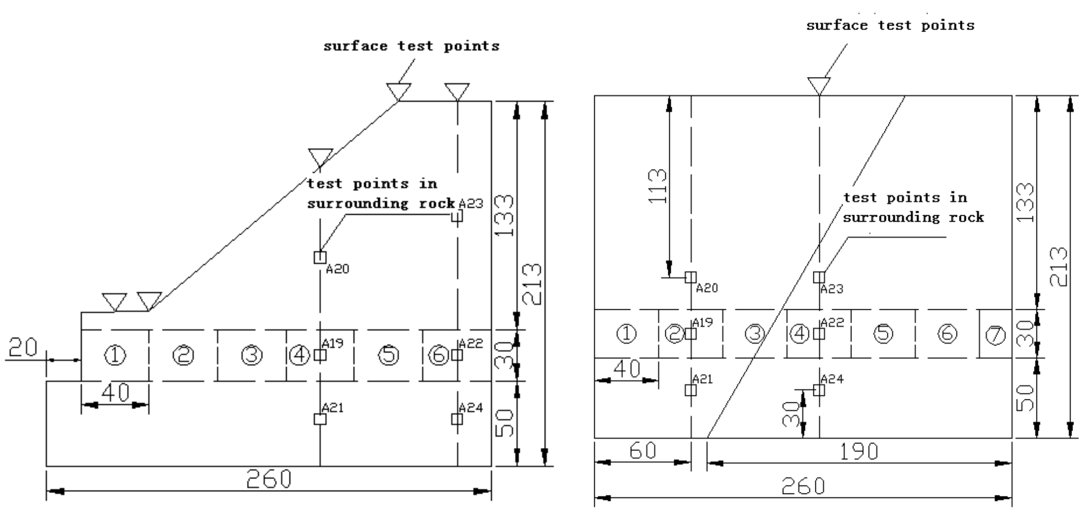
(1) Test point arrangement should be based on the purpose of this test;

(2) The limit of the testing ground, equipment and other conditions should be considered for the test point arrangement;

(3) The sensor is preferably arranged based on the existing theory and numerical simulation results so that all measurement results can be compared with the results of numerical simulations;

(4) In the case of meeting the basic information collecting, minimize the number of arranged sensors so as to avoid affecting the integrity of the model because of the arrangement of the sensors and resulting in larger test errors.

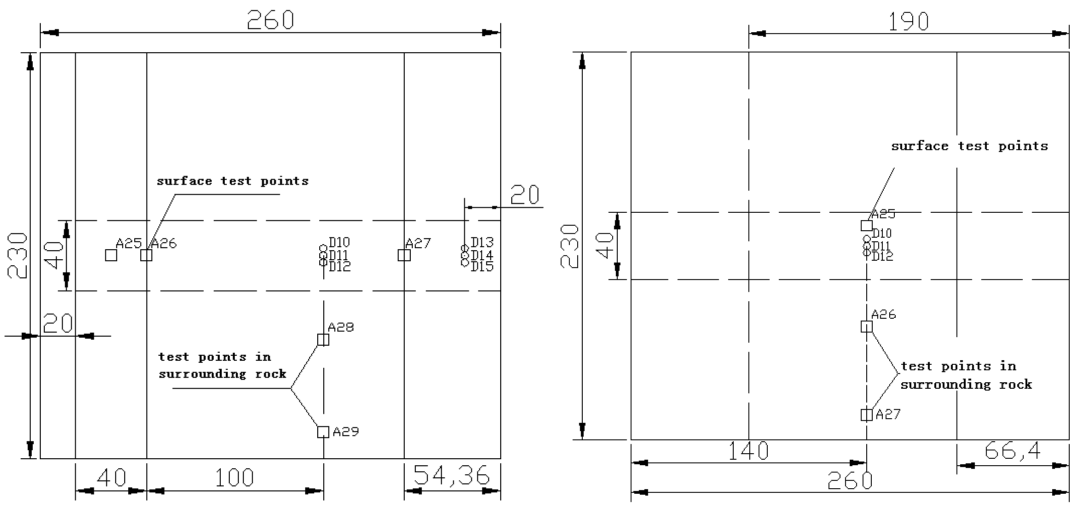
The front view of the tunnel and surrounding rock and the arrangement of test points are shown in Figure 4.



(a) Portal section (b) Tunnel body section

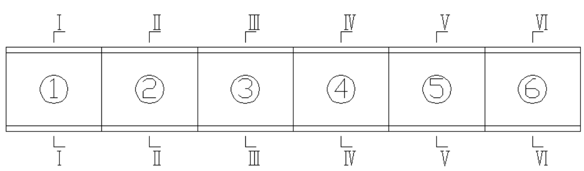
Figure 4. Front view of the arrangement of test points in tunnel and surrounding rock

According to the principles above, the top view of the tunnel and surrounding rock and the arrangement of the test points is as shown below in Figure 5:

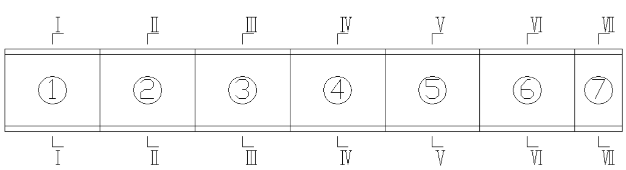


(a) Portal section (b) Tunnel body section

Figure 5. Top view of the arrangement of test points in tunnel and surrounding rock



(a) Portal section



(b) Tunnel body section

Figure 6. The layout of the tunnel structure

As can be seen from Figure 4(a) and Figure 5(a), in the portal section, on the surface a total of five test points longitudinally along the tunnel are arranged, the first, second and fourth test point respectively arranged an acceleration sensor, and the third and fifth test point respectively arranged a displacement sensors in three directions. Can also be seen from Figure 4(a), in the middle of 4th and 6th section, three test points are arranged along the vertical direction at the outer surface of lumbar arch in the rock, and each test point is arranged an acceleration sensors. As is shown in Figure 4(b) and Figure 5(b), in the tunnel body section, on the surface only one test point is arranged, and at this point, an acceleration sensor and a displacement sensors in three directions are arranged. Figure 4(b) is showing that in the middle of 2nd and 4th section, three test points are arranged along the vertical direction at the outer surface of lumbar arch in the rock, and each test point is arranged an acceleration sensors. In Figure 5, we can see that in the middle of the 4th section, two test points are arranged along the horizontal direction at the outer surface of lumbar arch in the rock both in the portal section and the tunnel body section, and each test point is arranged an acceleration sensors to verify the treatment effect of model box boundary. Figure 6 shows that both in the portal section and the tunnel body section, longitudinally along the tunnel a total of six typical observation sections are arranged, and the arrangement of each test point of the observation sections is as shown below in Figure 7:

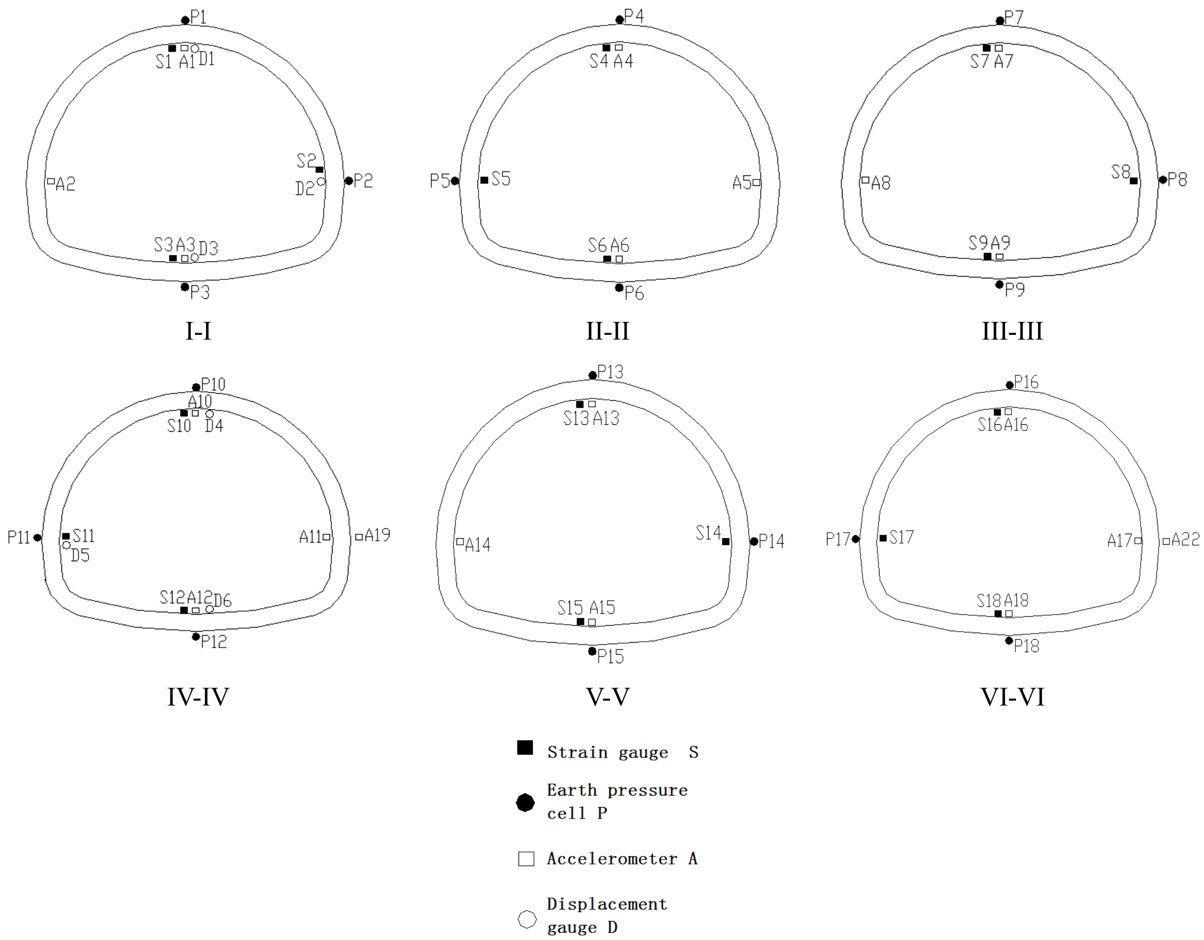


Figure 7. Sectional view of observation sections

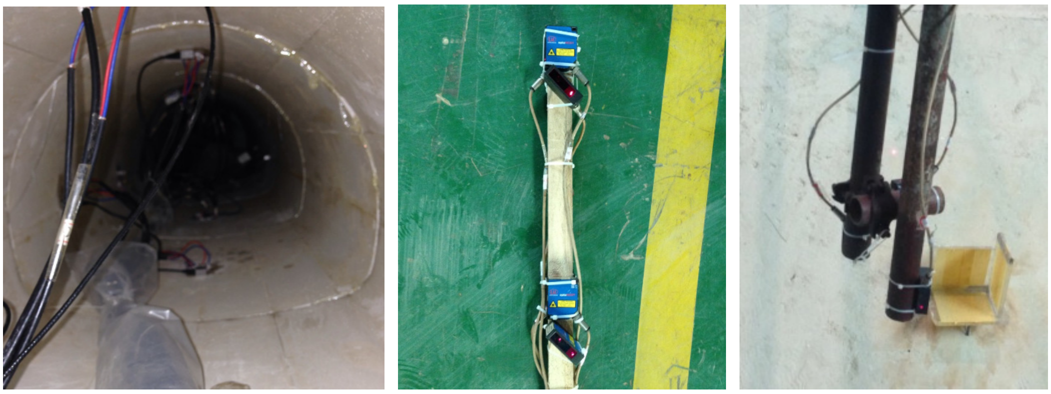


Figure 8. Sensor Installation

The quantities of apparatus in the portal section are shown in Table 3. Table 4 shows the quantities of apparatus in the tunnel body section.

Table 3. Quantities of apparatus in the portal section

Sections	Apparatus			
	Accelerometer	Strain gauge	Earth pressure cell	Displacement gauge
I-I	3	3	3	3
II-II	3	3	3	
III-III	3	3	3	
IV-IV	3	3	3	3
V-V	3	3	3	
VI-VI	3	3	3	
Ground surface	3			6
Surrounding rock	8			
Total	29	18	18	12

Table 4. Quantities of apparatus in the tunnel body section

Sections	Apparatus			
	Accelerometer	Strain gauge	Earth pressure cell	Displacement gauge
I-I	3	3	3	3
II-II	3	3	3	
III-III	3	3	3	
IV-IV	3	3	3	3
V-V	3	3	3	
VI-VI	3	3	3	
Ground surface	1			3
Surrounding rock	8			
Total	27	18	18	9

7. Loading Scheme

Shaking table test should use multiple hierarchical loading ways. The loading principles are as following:

(1) Estimate the successive input table acceleration amplitude based on the model's theoretical elastic and inelastic seismic response;

(2) At elastic stage, input a time history of a certain ground motion acceleration to test the model's seismic response amplification coefficient and elastic properties;

(3) At inelastic stage, increase the amplitude of the input acceleration to make gradual development of the specimen cracking moderately, meanwhile collect the test data and view the cracking or destruction of each part of the specimen;

(4) At failure stage, increase the amplitude of the input acceleration or input a certain peak acceleration repeatedly until the specimen is destroyed to test the seismic capacity of the test specimen.

Based on the test purposes and past experience, we use multiple hierarchical loading ways. The time intervals and peak acceleration was adjusted according to the similarity relationships. The test uses interval 0.00365s. We start with a small amplitude white noise for pre-vibration before intense vibrations, so that the model soil become compact, then the fundamental frequency and damping ratio of the system is obtained. We input white noise to scan at each subsequent change of input peak acceleration to observe the model changes of dynamic characteristics. The specific loading scheme of shaking table test is in Table 5.

8. Analysis of Test Results

Large amounts of data is obtained in the model test, but this paper only lists some representative record results of the load order 30 inputting seismic waves of Landers earthquake in Table 5 in the portal section because of the limited space. The results of the 4th section in the portal section model are listed in the following figures. The other detailed analysis of the results data can be referred to other papers. In this chosen condition, the seismic waves are input from X, Y, Z three directions simultaneously. Figure 9 to Figure 11 are the acceleration time histories of test points of the 4th lining and shaking table. In the condition, the peak accelerations of the 4th lining arch crown are 0.503g in X-direction, 0.83g in Y-direction and 0.473 g in Z-direction. The peak accelerations of the 4th lining arch shoulder are 0.397 g in X-direction, 0.689 g in Y-direction and 0.492 g in Z-direction. The peak accelerations of the 4th lining invert arch are 0.403 g in X-direction, 0.669 g in Y-direction and 0.462 g in Z-direction.

Table 5. Loading scheme of shaking table test

Load order	Waveforms	Recording stations	Amplitude adjustment coefficients	Peak acceleration (m/s^2)			Duration (s)	
				X-direction	Y-direction	Z-direction	Origin	Model
1	White noise	/	/	/	/	/	/	/
2	Kocaeli, Turkey	Duzce	1/5	—	0.716	—	27.18	4.96
3				0.624	—	—		
4				—	—	0.458		
5				0.624	0.716	0.458		
6	White noise	/	/	/	/	/	/	/
7	Landers, USA	Cool water	1/5	—	0.834	—	27.96	5.10
8				0.566	—	—		
9				—	—	0.347		
10				0.566	0.834	0.347		
11	White noise	/	/	/	/	/	/	/
12	Chichi	Tcu52	1/5	—	0.838	—	90.00	16.42
13				0.696	—	—		
14				—	—	0.482		
15				0.696	0.838	0.482		
16		Tcu68	1/5	—	1.132	—	90.00	16.42
17				0.924	—	—		
18				—	—	0.972		
19				0.924	1.132	0.972		
20	White noise	/	/	/	/	/	/	/
21	Kobe, Japan	Takarazuka	1/5	—	1.388	—	40.95	7.47
22				1.386	—	—		
23				—	—	0.866		
24				1.386	1.388	0.866		
25	White noise	/	/	/	/	/	/	/
26	Kocaeli, Turkey	Duzce	1	—	3.580	—	27.18	4.96
27				3.120	3.580	2.290		
28	White noise	/	/	/	/	/	/	/
29	Landers, USA	Cool water	1	—	4.169	—	27.96	5.10
30				2.828	4.169	1.736		
31	White noise	/	/	/	/	/	/	/
32	Chichi	Tcu52	1	—	4.190	—	90.00	16.42
33				3.480	4.190	2.410		
34		Tcu68	1	—	5.660	—	90.00	16.42
35				4.620	5.660	4.860		
36	White noise	/	/	/	/	/	/	/
37	Kobe, Japan	Takarazuka	1	—	6.940	—	40.95	7.47
38				6.930	6.940	4.330		
39	White noise	/	/	/	/	/	/	/

Note: X-direction is the direction of the tunnel cross section; Y-direction is the tunnel axis direction; Z-direction is vertical direction.

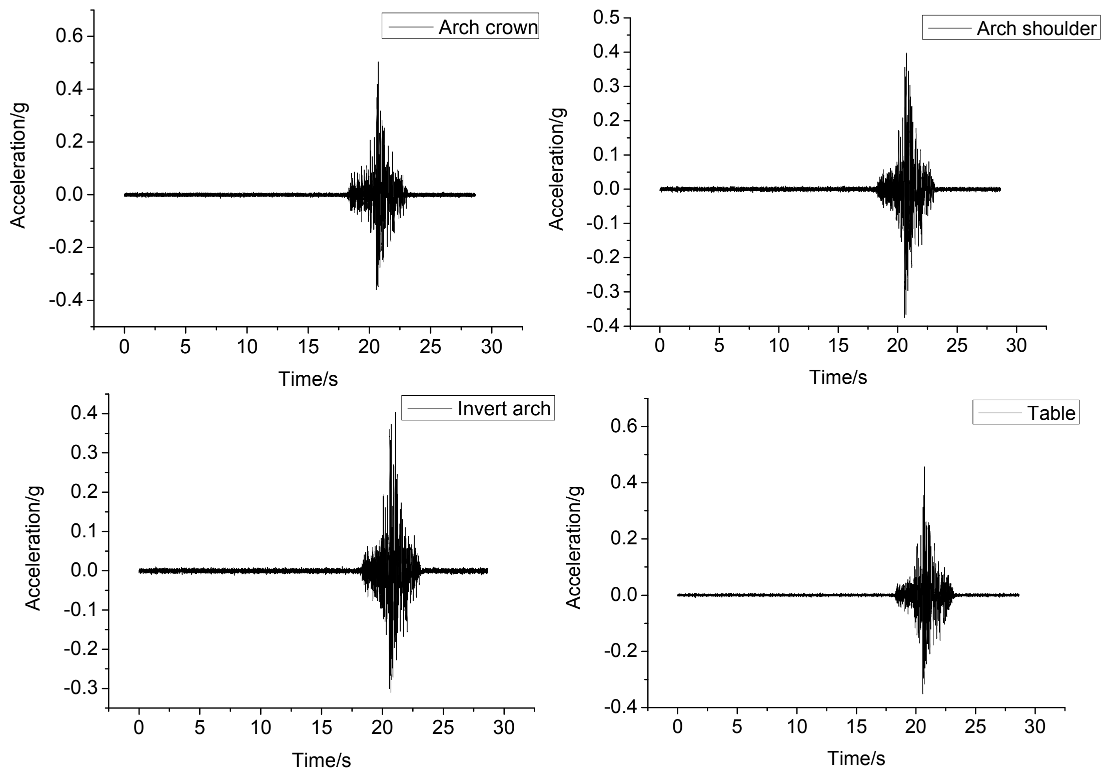


Figure 9. Acceleration time histories of model and shaking table in X-direction

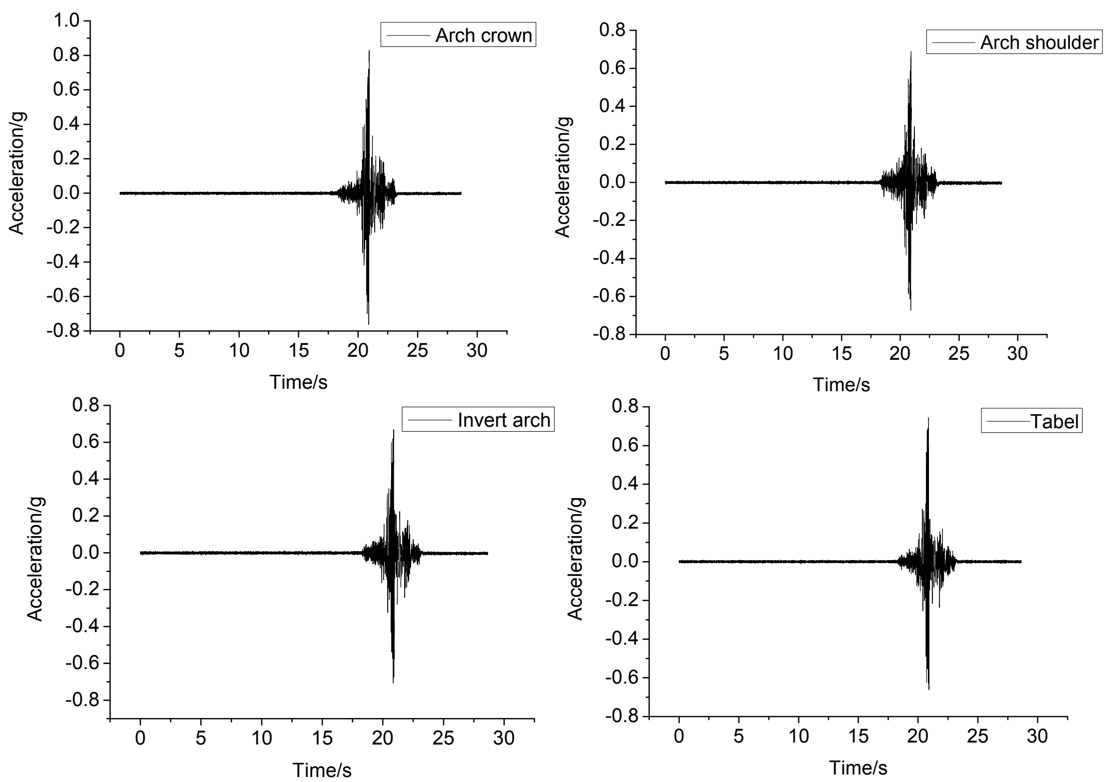


Figure 10. Acceleration time histories of model and shaking table in Y-direction

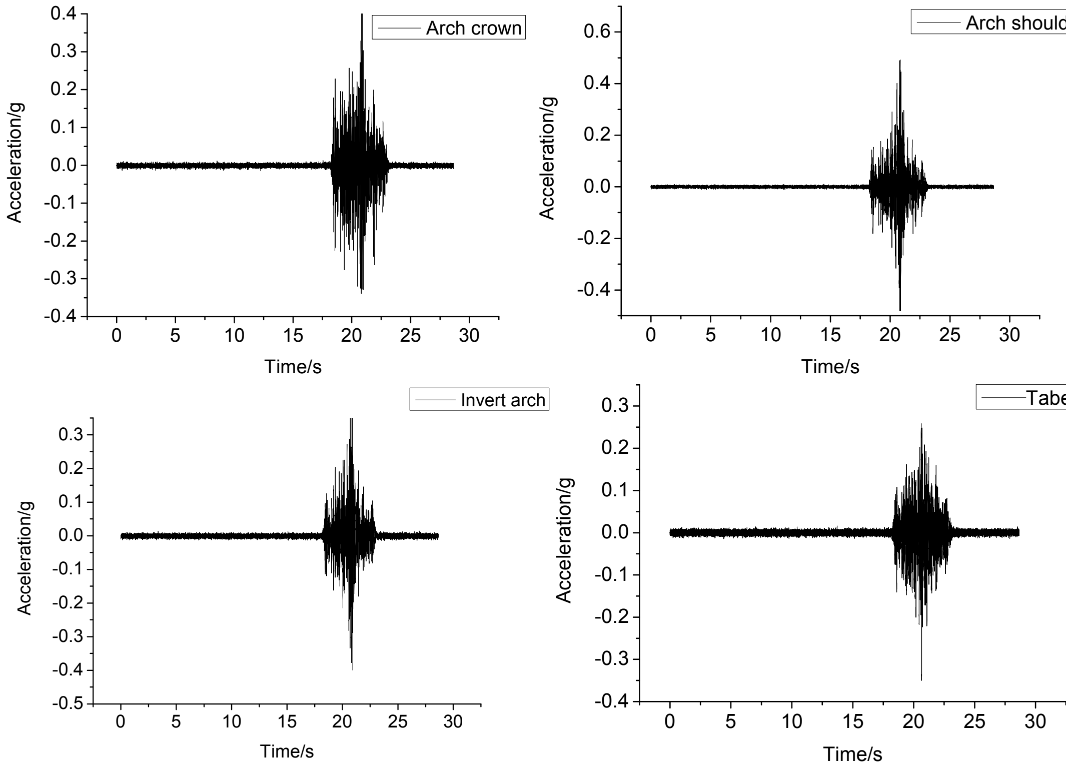


Figure 11. Acceleration time histories of model and shaking table in Z-direction

Figure 12 shows the earth pressures of the 4th lining model in different positions. The earth pressure of arch crown has a significant fluctuation in which the peak pressure is 4.26×10^{-3} MPa at the moment 22 s, while the earth pressures of arch shoulder and invert have small fluctuations in which the peak pressure also occurred at the moment 22 s.

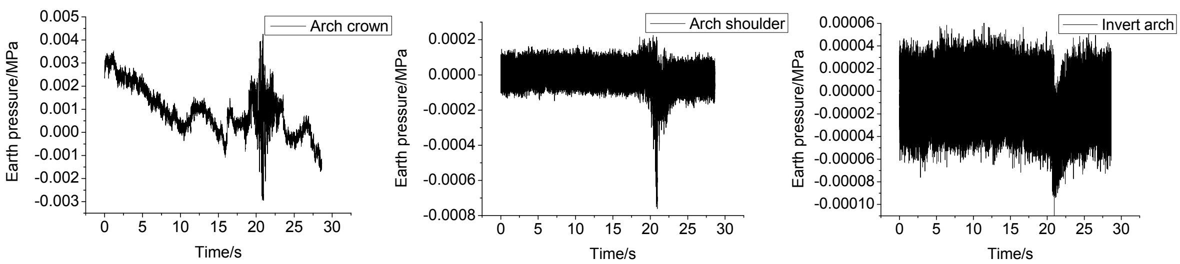


Figure 12. Earth pressure time histories of the surrounding rock in different places

Pictures in Figure 13 are the displacement time histories of different test points of the 4th lining model. The arch shoulder has the maximum displacement of 4 mm at the moment 20 s. In the third picture, the displacement of invert arch changes from 0mm to -1.5 mm finally. And in the first picture, the displacement of arch crown changes from 0mm to 0.3 mm. It is evident that the 4th lining model has a permanent deformation after the strong vibration.

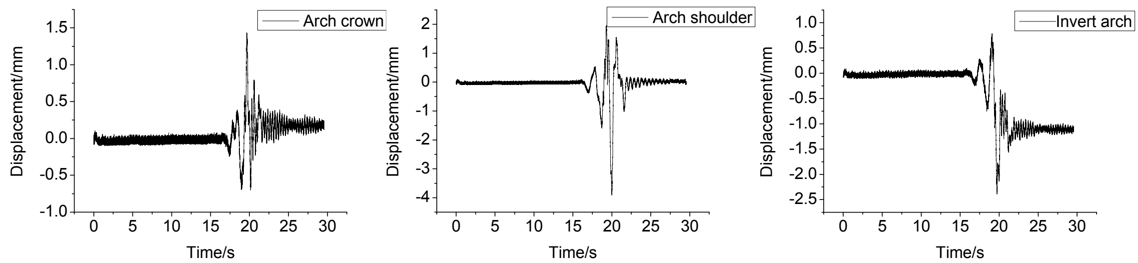


Figure 13. Displacement time histories of different test points of the 4th lining model

The peak acceleration variation of the 4th lining model with the increase of seismic waves is shown in Figure 14 in which the contrast of peak accelerations of arch crown, arch shoulder and invert arch when inputting different seismic waves is demonstrated.

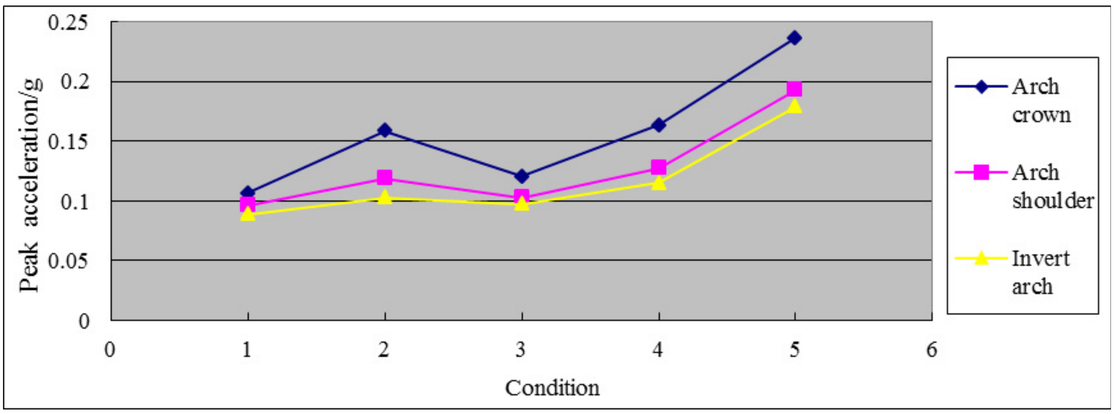


Figure 14. The acceleration variations of the 4th lining model with the increase of seismic waves

9. Summary and Conclusions

In this paper, research on a shaking table model test scheme of tunnel subjected to near-fault pulse-like ground motions is carried out based on the Natural Science Foundation Project of China "Theoretical study on shock absorption of tunnel subjected to near-fault pulse-like ground motions". The paper lays emphasis on the details of the design of the test scheme which contain the model similarity ratio, model box, model boundaries, the similar material of surrounding rock and lining, testing apparatus and test point arrangement and loading scheme. The following conclusions can be drawn from this research:

(1) Near-fault pulse-like ground motions is destructive to tunnel structures.

(2) Seismic responses of surrounding rock and lining soil increase with the upward propagation of seismic waves. Arch crown has larger accelerations and displacements than arch shoulder and invert arch. This should be taken into consideration in the tunnel's anti-seismic structure design.

(3) Cracks occur on the side slope above the tunnel and near the tunnel portal. Therefore, taking some anti-seismic measures of side slope is necessary for those tunnels in near-fault high-intensity earthquake area.

(4) In the same condition, the acceleration of arch crown varies with a trend of increasing along the tunnel in the portal section while the accelerations of arch shoulder and invert arch variation trends are not obvious.

References

Alavi, B., & Krawinkler, H. (2000, March). Design considerations for near-fault ground motions. In *Proceedings of the US–Japan Workshop on the Effects of Near-Fault Earthquake Shaking* (pp. 20-21).

Bray, J. D., & Rodriguez-Marek, A. (2013). Characterization of forward-directivity ground motions in the near-fault region. *Soil Dynamics and Earthquake Engineering, 24*(11), 815-828. http://dx.doi.org/10.1016/j.soildyn.2004.05.001

Chen, G., Zhuang, H., Du, X., Li, L., & Cheng, S. (2007). Analysis of large-scale shaking table test of dynamic soil-subway station interaction. *Earthquake Engineering and Engineering Vibration, 27*(2), 171-176.

Fang, L., Jiang, S., Lin, Z., & Wang, F. (2011). Shaking table model test scheme study on the tunnel through fault. *Rock and Soil Mechanics, 32*(9), 2709-2713.

Khoshnoudian, F., Ahmadi, E., & Sohrabi, S. (2014). Response of nonlinear soil-MDOF structure systems subjected to distinct frequency-content components of near-fault ground motions. *Earthquake Engineering & Structural Dynamics, 43*(5), 701-716. http://dx.doi.org/10.1002/eqe.2367

Lou, M., Wang, W., Ma, H., & Zhu, T. (2001). Study on soil-pile-structure interaction system by shaking table model test. *Journal of Tongji University, 29*(7), 763-768.

Martinelli, P., & Filippou, F. (2009). Simulation of the shaking table test of a seven-story shear wall building. *Earthquake Engineering & Structural Dynamics, 38*(5), 587-607. http://dx.doi.org/10.1002/eqe.897

Moustafa, A., & Takewaki, I. (2010). Characterization and modeling of near-fault pulse-like strong ground motion via damage-based critical excitation method. *Structural Engineering and Mechanics, 34*(6), 755-778. http://dx.doi.org/10.12989/sem.2010.34.6.755

Phillips, B. M., Wierschem, N. E., & Spencer, B. F. (2014). Model-based multi-metric control of uniaxial shake tables. *Earthquake Engineering & Structural Dynamics, 43*(5), 681-699. http://dx.doi.org/10.1002/eqe.2366

Shang, S, Liu, F., Lu, H., & Du, Y. (2006). Design and experimental study of a model soil used for shaking table test. *Earthquake Engineering and Engineering Vibration, 26*(4), 199-204.

Xie, L., Xu, L., & Rodriguez-Marek, A. (2005). Representation of near-fault pulse-type ground motions. *Earthquake Engineering and Engineering Vibration, 4*(2), 191-199. http://dx.doi.org/10.1007/s11803-005-0002-2